PLATFORM - A Journal of Engineering

Received: 17 August 2024, Revised: 7 October 2024, Accepted: 11 December 2024, Published: 31 December 2024, Publisher: UTP Press, Creative Commons: CC BY 4.0

QUANTITATIVE RISK ASSESSMENT IN THERMO-CHEMICAL WASTE-TO-ENERGY FACILITIES

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ABSTRACT

This study presents a Quantitative Risk Assessment (QRA) of thermo-chemical Waste-to-Energy (WtE) technologies, specifically incineration and gasification, by utilising simulation tools PHAST and SAFETI. Hazard identification, consequence analysis, and risk assessment were conducted to compare the safety profiles of these two technologies and proposed risk reduction strategies for a safer design. Accident scenarios were modelled for Tuas South Incineration and Borregaard Gasification facilities to analyse dispersion and effects of fire and explosion. Hazards indicated that only gasification exclusively involves flammable releases because it reacts as a partial combustion, with carbon monoxide and hydrogen as flammable byproducts. Results revealed that while gasification posed lower risks of toxic release, incineration exhibited lower fire and explosion risks. Individual risk fell within the ALARP region for both plants, with societal risk showing incineration falling within ALARP with a total risk integral of 0.000178/AvgYear but gasification nearing the unacceptable region with a total risk integral of 0.000586/AvgYear and a maximum potential average fatality of 8.5 and 24.5, respectively. Therefore, this risk assessment indicated that while both plants posed risks, incineration generally exhibited lower risks than gasification. Risk reduction measures such as leak detection and emergency response plans were recommended. This study enhances understanding of WtE risks, facilitating safety protocol improvements for a safer and sustainable WtE operation.

Keywords: *Consequence analysis, fire explosion, gasification, incineration, PHAST, SAFETI, safety, risk reduction, toxicity*

INTRODUCTION

Worldwide energy demand has risen quickly over the previous century, in tandem with growing living standards and waste production. Global population growth must be environmentally and economically feasible, with prompt action taken to tackle climate change [1]. Therefore, the two major concerns that mankind faces today are energy supply demand and waste management. A potential solution to both problems is Waste-to-Energy (WtE) technology. WtE is a waste. Waste is converted into fuels that may be utilised to produce energy in management techniques [2]. WtE conversion is accomplished through thermo-chemical, bio-chemical, and chemical [3]. Yet, this research focuses on recovery by heat in thermo-chemical processes, and the possible techniques include incineration and gasification, as shown in Table 1.

Incineration involves burning municipal solid waste (MSW) at 850°C in the full presence of oxygen, reducing its weight and volume while generating heat and energy. It is widely used in WtE applications and employs technologies such as grate incinerators, rotary kilns, and fluidised beds (Figure 1). Despite its economic and social benefits, incineration releases hazardous pollutants, including sulphur oxides (SO_x), carbon oxides (CO_x), nitrogen oxides (NO_x), and polyaromatic hydrocarbons (PAHs), which require advanced flue-gas treatment. Additionally, significant amounts of carbon dioxide are emitted during the process, presenting environmental and safety concerns.

Gasification is a partial oxidation process that converts carbon-rich materials into syngas, a high-calorific

Table 1 General comparison between incineration and gasification [4]-[6]

Factors	Incineration	Gasification
Reaction	Full oxidative combustion (O_2)	Partial oxidative combustion (O_2)
Benefits	Suitable for high caloric value and reduced volume up to 80%	Production of fuel gas/oil, which can be used for various purposes
Limitation	Produce harmful pollutants of solid residues	Inflexible, less competitive, and produces flammable gases
Primary Product	Heat	Syngas producer gas
Temperature	800 – 1450°C	500 – 1600°C
Pressure	Atmospheric	1 to 45 bar
Application	Generation of electricity, steam/heat, and chemicals	

mixture of hydrogen, carbon monoxide, and carbon dioxide. These syngas can be utilised for energy production or as a feedstock for chemicals like methanol and dimethyl ether. Gasification operates by injecting controlled amounts of oxygen into a high-temperature reactor to produce syngas, which are later combusted separately for energy (Figure 2). Compared to incineration, gasification poses distinctive risks, such as potential leaks of flammable or toxic gases, though these risks are lower in traditional combustion processes where fuel is fully burned to generate stable byproducts. For instance, Japan employs gasification to process plastic packaging waste into synthesis gas.

Although WtE is appealing as a green methodology, it also has risks and hazards. Researchers have found that most of the process safety incidents in WtE come from thermo-chemical treatment plants, whose hazard parameters were initiated by toxicity, fire, and explosion [6]. For example, in 2016, a fire occurred in the Spokane plant of a four-story-high mound of junk that clogged the bays, and two workers were injured after being burnt while clearing out a boiler. A few explosion cases occurred in China, such as in Shanghai (2013) and Guangzhou (2010), created public dissatisfaction with WtE facilities in residential areas.

Quantitative Risk Assessment (QRA) is a comprehensive method for identifying and managing risks by estimating the chance and potential effects [6]. Figure 3 illustrates the general framework of QRA. This procedure helps to assess and quantify the risks associated with a certain system, facility, or activity. It entailed identifying the possible hazards by evaluating their likelihood and implications and establishing the amount of risk they pose. It is found from the literature that statistical and mathematical methods have been used and that this knowledge can be employed to make decisions regarding risk reduction strategies [9]. Due to significant gaps in the literature on WtE technologies and a limited number of studies on the subject, QRA is thus the primary approach employed in this study to evaluate the risk of WtE technologies from various WtE facilities.

QRA is a methodical and analytical approach to assessing and estimating risks associated with multiple operations, events, or systems. It employs mathematical and statistical methodologies to evaluate the likelihood and consequences of potential risks or catastrophic occurrences [13]-[14]. QRA aims to provide a quantified risk assessment, allowing decision-makers to effectively prioritise and allocate resources for risk management

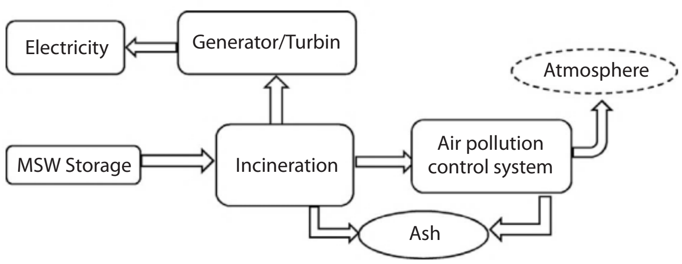

Figure 1 Schematic of the incineration process [4]

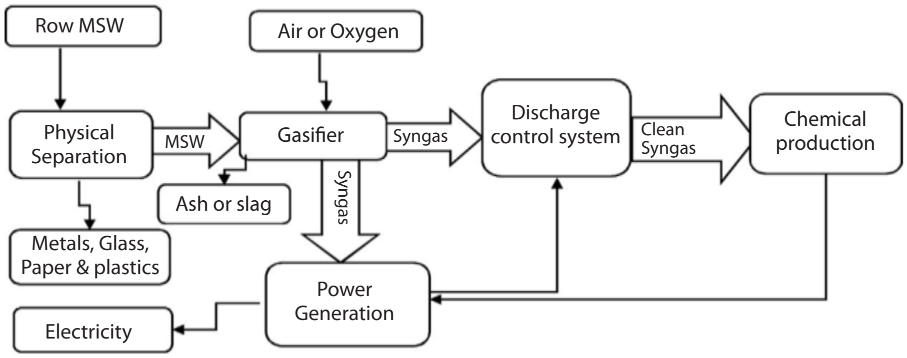

Figure 2 Schematic of gasification plant [4]

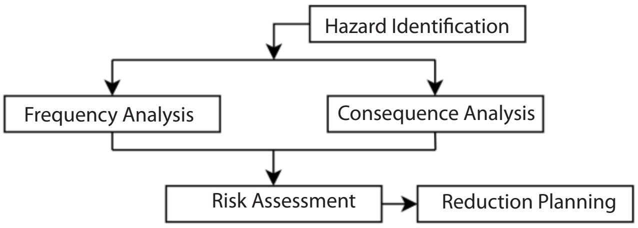

Figure 3 General QRA framework

and mitigation approaches. This technique includes identifying effects and analysing subsequent hazards, predicting their chance of occurrence, and establishing the possible severity of their consequences [13]-[14].

Individual Risk Analysis

Individual Risk Assessment evaluates potential harm to individuals from various hazards, often quantified as Individual Risk Per Annum (IRPA). IRPA, expressed as a probability, measures the likelihood of harm occurring to an individual within a year and is central to process safety [15]. Risk management employs the As Low As Reasonably Practicable (ALARP) principle, which balances the likelihood and severity of risks to ensure reasonable safety measures [16]. Within this framework, several distinct zones or regions are delineated (Figure 4).

Societal Risk Analysis

Societal Risk Assessment examines risks impacting communities, considering population density, vulnerability, and activity importance [15]. The F-N curve illustrates the relationship between the frequency of hazardous events and the number of fatalities, with the ALARP region lying between minimum and maximum criterion lines. This region emphasises balancing risk reduction and practicality in health, safety, and environmental contexts [15]-[16]. Potential Loss of Life (PLL) estimates the expected annual fatalities within a population or area, often segmenting populations to identify higher-risk groups. PLL aids in assessing casualty severity across scenarios and can be linked to Individual Risk Per Annum (IRPA), which provides annual fatality risk probabilities for individuals. These metrics guide effective risk control and reduction strategies [15]-[16].

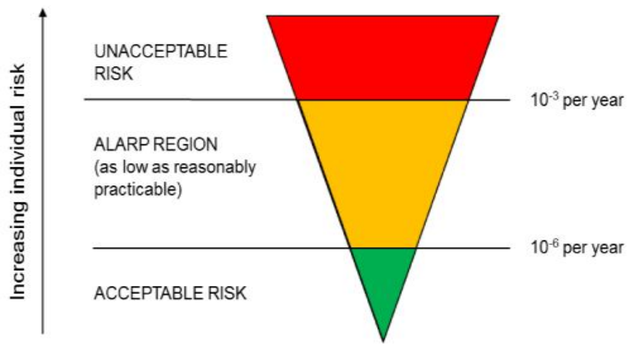

Figure 4 Risk acceptance framework from the Department of Environment (DOE) [7]

Material Safety Data Sheets

Material Safety Data Sheets (MSDS) provide crucial information on the hazards and parameter limitations, which are essential for ensuring safety and compliance during processes in incineration and gasification (Table 2).

Based on the MSDS, it can be concluded that the identified hazards show that gasification specifically involves flammable emissions due to its nature as a partial combustion process, producing carbon monoxide and hydrogen as flammable byproducts. This flammability impact of these two facilities is supported by arguments from the literature, which stated that

Table 2 Summary of hazards associated with substances in incineration and gasification plants [11]

Substance	Carbon Dioxide	Carbon Monoxide	Hydrogen
Hazard statements	1. It may explode if heated. 2. It may cause rapid suffocation. 3. It may increase the respiration rate.	1. Extremely flammable gas 2. It may explode if heated 3. May damage fertility	1. Extremely flammable gas 2. It may explode if heated 3. May form explosive mixtures
LEL and UEL	It does not sustain flammability	Lower: 10.9% Upper: 74.2%	Lower: 4% Upper: 76%
Auto-ignition temp		607°C	500°C to 571°C
NFPA Ratings			
Substance	Hydrogen Chloride	Nitrogen Dioxide	Sulphur Dioxide
Hazard statements	1. It may explode if heated 2. Toxic if inhaled 3. It may cause respiratory irritation	1. May cause or intensify fire 2. It may explode if heated 3. Causes severe skin burns	1. It may explode if heated 2. Causes severe skin burns 3. Toxic if inhaled
LEL and UEL		It does not sustain flammability.	
Auto-ignition temp			
NFPA Ratings			

there is no flammable gas generated in incineration with a high indication of flammable mixture potential in gasification [6].

There is a notable lack of comprehensive QRA in WtE facilities, particularly regarding the risks associated with equipment and materials. While some studies have explored related issues, such as comparing Safety, Health, and Environment (SHE) for WtE technology selection, these efforts are limited. Previous research identified sulphur dioxide and furan as the most hazardous compounds in incineration and carbon monoxide and hydrogen as flammable factors in gasification [7]. However, no QRA has specifically discussed this issue. To address this gap, this study utilises PHAST SAFETI simulation to assess and compare the safety levels of equipment and materials involved. The study aims to identify hazard parameters influencing safety, quantify and compare risks across technologies, and propose effective risk reduction strategies. These findings will improve safety measures and guide the development of safer WtE facilities.

METHODOLOGY

Overall Flowchart

The methodology (Figure 5) displays first the type of WtE technology that was defined, and hazards and relevant parameters were identified. Hypothetical accident scenarios were created, followed by data gathering on operational parameters, leak sizes, and environmental factors. Toxic release, fire, and explosion scenarios were modelled in PHAST, with adjustments made if the results were unsatisfactory. The findings were validated against safety standards and integrated into SAFETI, which assessed individual risk (IRPA) and societal risk (F-N curves, PLL). The results were compared, and risk mitigation strategies were proposed before concluding the study.

Facilities for Each WtE Technologies

For incineration, Tuas South Incineration Plant (Figure 6), located in Singapore, was chosen as it is the fourth and largest WtE incineration plant in Singapore and is designed to incinerate 3,000 tonnes

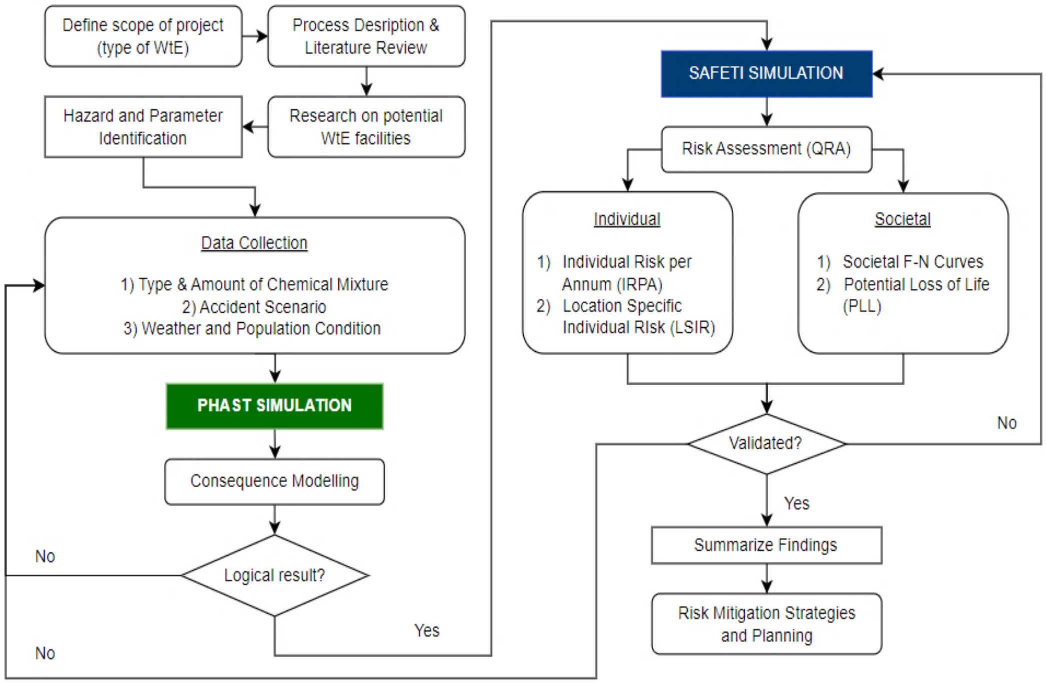

Figure 5 Flowchart of overall research methodology

Figure 6 Map location of Tuas South Incineration Plant [17]

Figure 7 Map location of Borregaard Sarpsborg 2 Plant [18]

of waste daily, achieving about 90% reduction in the volume of the refuse. The Borregaard Sarpsborg 2 Plant (Figure 7), located in Norway, was chosen for gasification as it is the only gasification plant near the residential area. This plant has been producing 256 GWh per annum, displacing around 22,000 tonnes of fossil fuel annually through its sophisticated gasification chamber.

Data Collection

The QRA analysis was based on assumptions from the literature and adjusted data, including material and equipment properties from trusted sources, mass inventory from plant waste input, and weather conditions from historical data. Only catastrophic rupture and leak scenarios were considered, with population data sourced from available information.

Data for PHAST Simulation

Operating Condition

Tables 3 and 4 summarise the basic plant parameters for Tuas South Incineration Plant facilities and the Borregaard Sarpsborg 2 plant.

Weather Condition

For each facility, the parameter set value for weather conditions is shown in Table 5, in which the average wind speed is utilised to find the stability class based on Figure 8.

Orifice Diameter and Accident Scenario

Two types of scenarios were studied based on the equipment and materials involved. A catastrophic rupture involves an instantaneous, large-scale release of hazardous materials due to sudden, complete failure,

Table 3 Operating condition for Tuas South Incineration [17],[19]

Materials	Fraction Amount		
Carbon Dioxide, CO_2	0.30		
Nitrogen Dioxide, NO_2	0.30		
Sulphur Dioxide, SO_2	0.10		
Hydrogen Chloride, HCl	0.10		
Chlorine, Cl	0.10		
Water, H_2O	0.10		
Equipment	Capacity	Temperature	Pressure
Furnace Stoker	300 tons/day	840°C	3 bar
Superheater Boiler	300 tons/day	900°C	5 bar

Table 4 Operating condition for Borregaard Sarpsborg 2 [20]-[21]

Materials	Fraction Amount		
Carbon Monoxide, CO	0.40		
Hydrogen, H_2	0.20		
Nitrogen Dioxide, NO_2	0.15		
Sulphur Dioxide, SO_2	0.10		
Methane, CH_4	0.05		
Equipment	Capacity	Temperature	Pressure
Primary Gasifier	100 tons/day	750°C	18.1 bar
Secondary Chamber	100 tons/day	950°C	30.0 bar

Table 5 Parameter set value for weather conditions [22]

WtE Technology	Incineration		Gasification
Atmospheric Temperature		9.85	
Relative Humidity (Fraction)		0.7	
	Calm-Case		
Wind Speed	< 2.0 mph = < 1.5 m/s		< 2.0 mph = < 1.5 m/s
Time of Day		Night	
Radiation intensity		Calm & Clear	
Stability Class		1.0/F (Moderately Stable)	
	Worst-Case		
Wind Speed	6.6 mph = ~ 2 - 3 m/s		6.9 mph = ~ 2 - 3 m/s
Time of Day		Day	
Radiation intensity		Strong - Medium	
Stability Class		2.5/A - B (Extremely ~ Moderately Unstable)	

lasting for a short period. In contrast, a leak scenario involves a continuous, smaller release over a more extended period, typically caused by equipment failure or maintenance issues. The leak sizes for both facilities in each scenario are shown in Table 6.

Data for SAFETI Simulation

Event Frequency

The event frequency should be obtained prior calculating the risk integral. The data for event frequency can be found as shown in Figure 9.

Wind speed (m/s)	Day radiation intensity			Night cloud cover	
	Strong	Medium	Slight	Cloudy	Calm & clear
< 2	A	A – B	B	F	F
2 – 3	A – B	B	C	E	E
3 – 5	B	B – C	C	D	E
5 – 6	C	C – D	D	D	D
> 6	C	D	C	D	D

A : Extremely unstable
B : Moderately unstable
C : Slightly unstable
D : Neutrally stable
E : Slightly stable
F : Moderately stable

Figure 8 Atmospheric stability classes with the Pasquill-Gifford Dispersion Model [14]

Table 6 Orifice diameter and accident scenario [23]

Accident Scenario	Orifice Diameter (mm)
Leak (Medium)	51
Catastrophic Rupture	> 152

Table 7 Event frequency for each scenario

Accident Scenario	Orifice Diameter (mm)	Event Frequency per year
Leak (Medium)	51	4.9×10^{-5}
Catastrophic Rupture	> 152	5.0×10^{-6}

Wind Direction Value
The wind flow from all cardinal directions can be obtained from literature [22]. Table 8 displays the data for wind direction for each of the weather conditions.

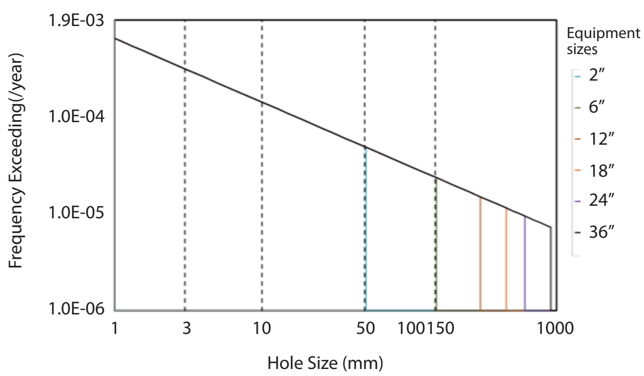

Figure 9 Event frequency vs hole size

Population Data
For population, the equation has been extracted from [24]. Tables 9 and 10 display the population data for incineration and gasification plants, respectively.

Ignition Source Condition
From Table 11, the data need to be acquired, given that the ignition probability for the ignition polygon is 0.9 and the transportation polyline is 0.2 [25].

Table 8 Wind direction condition [22]

Weather Condition	Wind Direction							
	N	NE	E	SE	S	SW	W	NW
	Tuas South Incineration Plant, Singapore							
Day: 2.5/A-B	22.0%	17.0%	6.0%	10.0%	19.0%	10.0%	7.0%	11.0%
Night: 1.0/F	6.0%	10.0%	29.0%	5.0%	20.0%	21.0%	6.0%	3.0%
	Borregaard Sarpsborg 2 Gasification Plant, Norway							
Day: 2.5/A-B	10.0%	21.0%	14.0%	6.0%	19.0%	19.0%	6.0%	5.0%
Night: 1.0/F	9.0%	21.0%	14.0%	11.0%	16.0%	11.0%	6.0%	12.0%

Table 9 Population condition data for Tuas South Incineration

Area	Category	Number of populations		Fractions indoors	
		Day	Night	Day	Night
Process Area	Operators	23	12	0.5	0.8
Industrial Area	Operators	70	35	0.6	0.8
Industrial Office	Admin	30	15	0.8	0.9
Residential	Public	60	120	0.9	1.0

Table 10 Population condition data for Borregaard Gasification

Area	Category	Number of populations		Fractions indoors	
		Day	Night	Day	Night
Process Area	Operators	43	21	0.5	0.8
Industrial Area	Operators	30	15	0.6	0.8
Industrial Office	Admin	20	10	0.8	0.9
Residential	Public	40	80	0.9	1.0

Table 11 Ignition Source for Tuas South Incineration

Ignition Polygon			
Time	Area	Operating Operability	
Day	Process Area Industrial Area	1.0 1.0	
Night	Process Area Industrial Area	0.9 0.9	
In-time period	10 s	Ignition Probability	0.9
Transportation polyline			
Time	Area	Traffic Density	Average Speed
Day	Industrial Service Roads	80 / hr	60 m/s
Night	Industrial Service Roads	20 / hr	40 m/s
In-time period	10 s	Ignition Probability	0.2
Night	Industrial Service Roads Residential Roads	40 / hr 10 / hr	50 m/s 30 m/s
In-time period	10 s	Ignition Probability	0.2

PHAST and SAFETI Simulation

PHAST software v8.61 was used for the simulation, and Figure 10 outlines the steps to establish a case study, while SAFETI integrates PHAST for consequence analysis in Figure 11.

RESULTS AND DISCUSSIONS

Hazards Identification

Before conducting risk analysis using PHAST and SAFETI simulations, hazards for both plants were evaluated. From Table 13, the Tuas incineration plant involves only toxic materials: carbon dioxide, hydrogen chloride, nitrogen dioxide, and sulphur dioxide. In contrast, the Borregaard gasification plant includes both toxic (carbon monoxide, nitrogen dioxide, sulphur dioxide) and flammable releases (carbon monoxide, hydrogen). These findings are consistent with the MSDS in Chapter 1 (Table 2), which summarises the associated hazards.

Table 12 Ignition Source for Borregaard Gasification

Ignition Polygon			
Time	Area	Operating Operability	
Day	Process Area	1.0	Industrial Area 1.0
Night	Process Area	0.9	Industrial Area 0.9
In-time period	10 s	Ignition Probability	0.9
Transportation polyline			
Time	Area	Traffic Density	Average Speed
Day	Industrial Service Roads Residential Roads	100 / hr 50 / hr	60 m/s 50 m/s
Night	Industrial Service Roads Residential Roads	40 / hr 10 / hr	50 m/s 30 m/s
In-time period	10 s	Ignition Probability	0.2

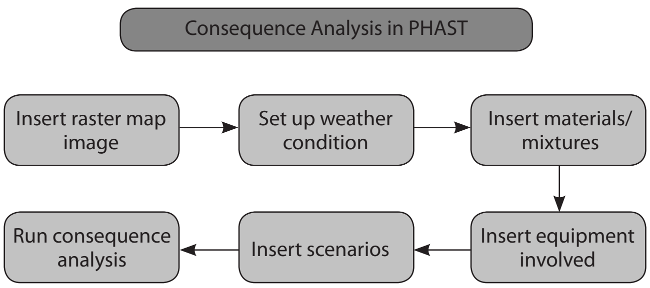

Figure 10 Steps to establish a case study in PHAST

Table 13 Summary of hazardous materials

Hazard Release	Tuas Incineration		Borregaard Gasification	
	Toxic	Flammable	Toxic	Flammable
Carbon Dioxide	✓			
Carbon Monoxide			✓	✓
Hydrogen				✓
Hydrogen Chloride	✓			
Nitrogen Dioxide	✓		✓	
Sulphur Dioxide	✓		✓	

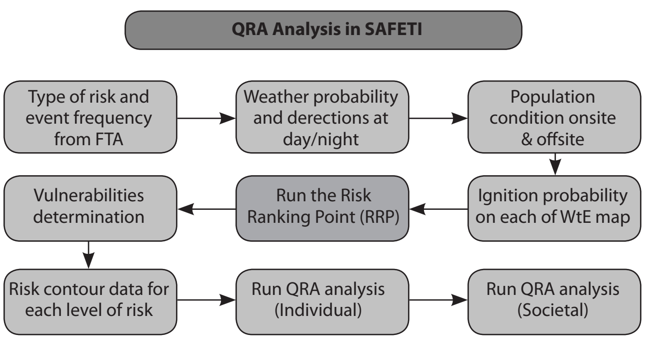

Figure 11 Steps to perform QRA in SAFETI

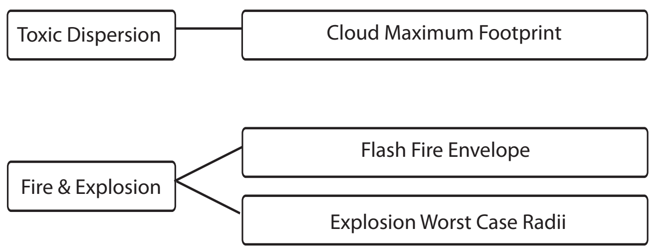

Figure 12 Output analysis for PHAST

Consequence Analysis from PHAST

In the consequence analysis, only the catastrophic rupture scenarios representing worst-case scenarios were analysed. As discussed in the Results and Discussion section, both plants will have toxic dispersion analysis; meanwhile, only the Borregaard gasification plant will have fire and explosion analysis. Several output analyses have been obtained under toxic dispersion and fire explosion, as shown in Figure 12.

Toxic Dispersion

For incineration, the Cloud Width vs Distance Downwind graphs (Figures 13 and 14) show toxic release footprints at 160.009 ppm under different wind speeds (1.0 m/s and 2.5 m/s) and stability conditions (F and A-B). The furnace stoker's risk increases with slower nighttime winds, with a cloud height of 498.5 m and a maximum travel distance of 5350 m. The superheated boiler shows similar behaviour, with a cloud height of 500 m and a distance of 5400 m. Both cases show higher

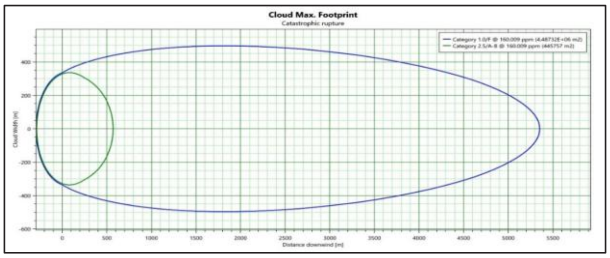

Figure 13 Cloud max footprint for furnace stoker

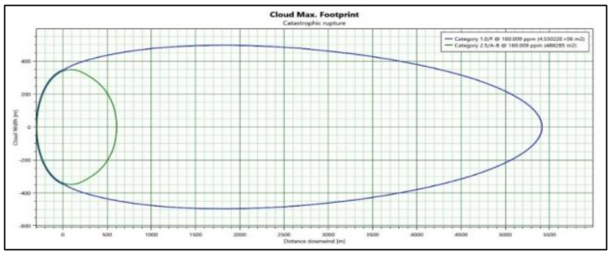

Figure 14 Cloud max footprint for superheated boiler

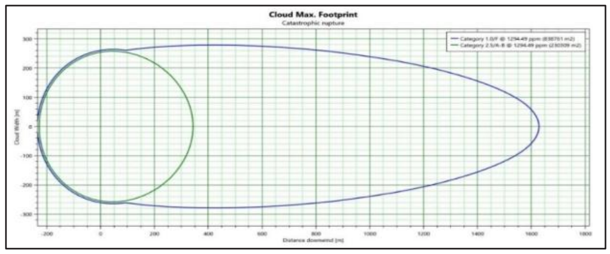

Figure 15 Cloud max footprint for primary gasifier

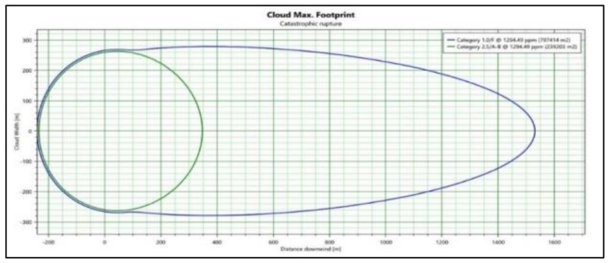

Figure 16 Cloud max footprint for oxidation chamber

risks during low wind speeds, with minimal differences in footprint behaviour. The graphs (Figures 15 and 16) show toxic release footprints at 1249.49 ppm for gasification. The primary gasifier's footprint reaches 279 m in height and 1625 m in distance, while the oxidation chamber measures 280 m and 1530 m. Both scenarios confirm higher risks during slower winds, with negligible differences in footprint behaviour.

A matrix analysis compared hazard robustness using downwind distance, cloud width, and maximum footprint area. The analysis focused on worst-case catastrophic ruptures, comparing the furnace stoker with a primary gasifier and superheated boiler with an oxidation chamber (Table 14). The binary values (1 – Less Hazardous; 0 – Hazardous) provide a simplified representation for comparison. The Cloud Maximum Footprint analysis shows that toxic cloud dispersion depends on plant type, substances, weather, terrain, and containment. Distance downwind reflects how far substances travel, with longer distances indicating higher risk zones. Incineration showed longer downwind distances than gasification. Cloud width, determining the affected area, was more significant in incineration, impacting larger areas. Area of dispersion combines both factors, with incineration covering larger zones, confirming its higher hazard potential for toxic releases.

Fire and Explosion

Flash Fire Envelope

A flash fire in the primary gasifier and oxidation chamber is a sudden, intense fire caused by the rapid ignition of flammable gases. A catastrophic failure

Table 14 Cloud Maximum Footprint Analysis

Facility		Incineration	Gasification	Incineration	Gasification
Equipment		Furnace Stoker	Primary Gasifier	Superheated Boiler	Oxidation Chamber
Cloud Maximum Footprint	Distance downwind	5350.0 m 0	1625.0 m 1	5400.5 m 0	1530.5 m 1
	Cloud width	498.5 m 0	279.2 m 1	500.5 m 0	280.1 m 1
	Area of dispersion	$4.49 \times 106\ m^2$ 0	$838761\ m^2$ 1	$4.56 \times 106\ m^2$ 0	$797414\ m^2$ 1

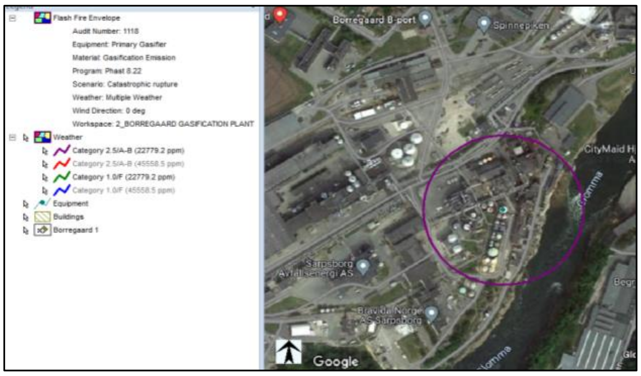

Figure 17 Flash fire envelope contour for primary gasifier

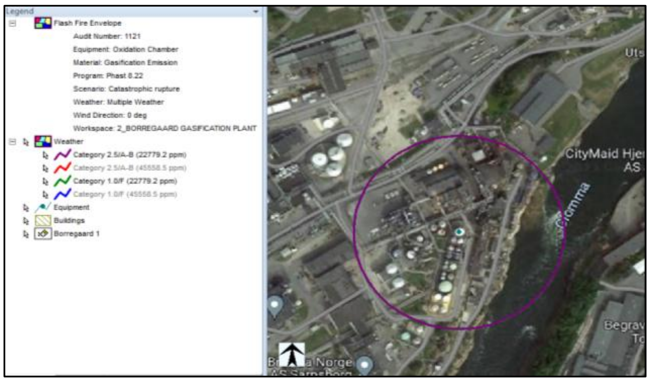

Figure 18 Flash fire envelope contour for oxidation chamber

releases gases that mix with air and ignite upon encountering a spark or flame, creating a flash fire. It notes that flash fires can cause severe burns and structural fires. For the primary gasifier, the flash fire's lower flammability limit (LFL) extends 132 m downwind with a concentration of 22779.2 ppm, exposing plant personnel and equipment within this radius to hazards. This limited area suggests a smaller public impact but significant risk to workers. The oxidation chamber has a larger flash fire LFL contour, extending 162.5 m, about 30 m further than the primary gasifier. This increased reach indicates a greater risk exposure zone, likely due to its larger capacity. Flash fires ignite rapidly within seconds of gas release and are highly unexpected, as seen in the catastrophic rupture scenario. GIS findings show that the flash fire envelope from a leak scenario would affect part of the production plant, exposing workers to potential injuries within that radius.

Explosion Worst Case Radii

Overpressure, known as a blast wave, occurs when a pressure wave exceeds atmospheric pressure due to an explosion. This phenomenon, termed explosion overpressure, can result in structural damage, injuries, fatalities, and other adverse effects. For the primary gasifier (Figure 19), the overpressure increases gradually from 1 bar to a peak of 20 bar within approximately 100 m from the leak site, posing significant risks to individuals and structures. Beyond this distance, the overpressure sharply declines to 2 bar at 180 m, consistent with the inverse square law, which states that overpressure decreases as the square of the distance increases [28]. These findings underscore the potential dangers of explosions and the importance of peak pressure in evaluating their impact. The behaviour of the oxidation chamber (Figure 20) is similar, with overpressure peaking at 20 bar within 110 m of the leak site before declining to 2.4 bar at 180 m. The larger gasifier, which likely contains more syngas, has the potential for more severe explosion impacts than smaller systems. However, the differences between the two scenarios are minimal, as they exhibit similarly hazardous overpressure patterns. These results emphasise the need for focused research on peak pressures in explosion effect modelling to understand better and mitigate the risks associated with such catastrophic events.

In consequence analysis, it is noted that fire and explosion are exclusively associated with gasification. Therefore, there is no requirement for a matrix calculation to evaluate the hazard robustness in this regard. Nevertheless, Table 15 compiled the result to analyse four key factors: distance downwind, distance crosswind, and the levels of radiation and overpressure. This analysis considers worst-case weather conditions, where the flash fire envelope's downwind and crosswind distances determine the area affected by radiation and overpressure. Higher wind speeds may extend the downwind distance of a vapour cloud but disperse it faster, influencing the flash fire envelope and giving more significant releases of flammable material, resulting in greater flash fire distances, higher radiation, and more severe overpressures. Since incineration lacks flammable material analysis, it presents fewer fire and explosion hazards than gasification.

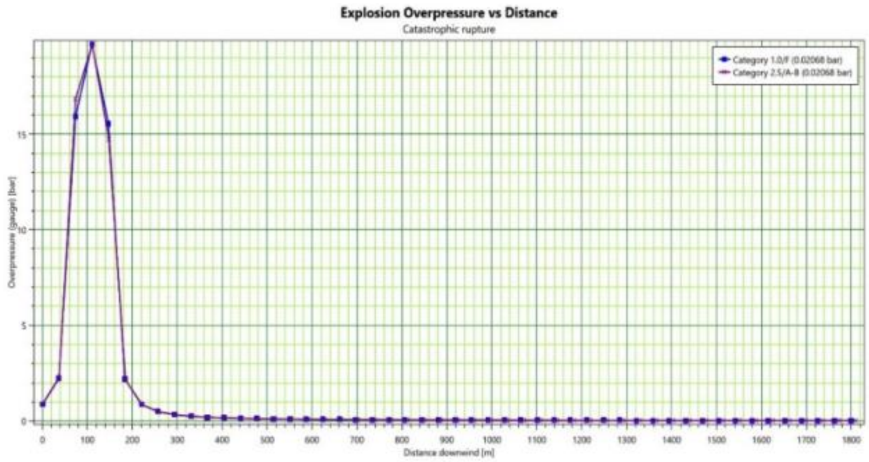

Figure 19 Explosion overpressure for primary gasifier

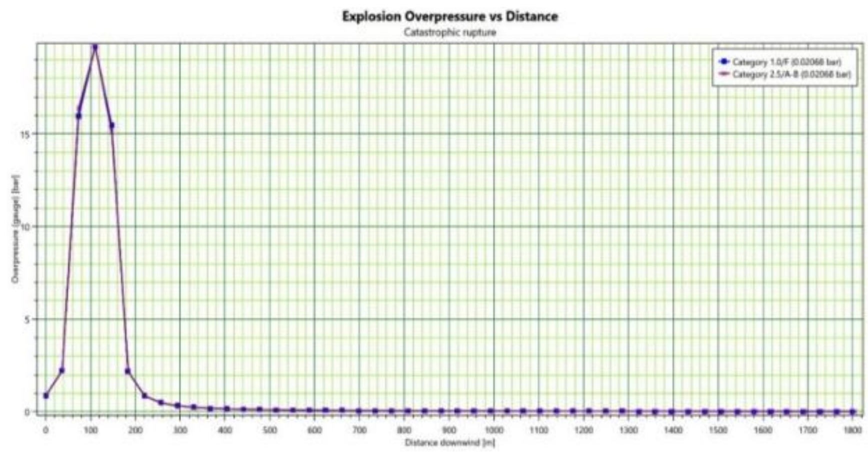

Figure 20 Explosion overpressure for oxidation chamber

Table 15 Fire and Explosion Consequence Analysis

Equipment		Primary Gasifier	Oxidation Chamber
Flash Fire Envelope	Distance downwind	131.5 m	162.5 m
	Distance crosswind	131.5 m	162.5 m
	Fireball Radiation	350 kW/m^2	400 kW/m^2
Explosion Worst Case Radii	Distance downwind	100.0 m	110.0 m
	Overpressure (gauge)	19.0 bar	20.0 bar

Risk Assessment from SAFETI

Individual Risk Analysis

Figure 21 illustrates individual risk contours (10^{-5} to 10^{-9} per year) for the incineration facility, with the contours extending beyond the plant boundary. The 10^{-5} contour spans most of the facility, showing higher risks indoors than outdoors. Malaysia's Department of Environment (DOE) states that risks exceeding 10^{-3} per year are deemed intolerable. While indoor risks are considered acceptable, the risks outdoors require mitigation, following ALARP principles, to reduce the potential hazards. The highest calculated risk is 2.193×10^{-5} per year, highlighting the need for precautionary measures in worst-case scenarios of catastrophic rupture.

Figure 22 presents the risk contours for gasification, which are larger than those of the incineration facility. The 10^{-5} contour almost covers the entire facility and extends beyond its boundary, with higher contours (10^{-6} to 10^{-9}) affecting an even larger area. The increased risk for gasification is primarily due to higher operating pressures (18–30 bar) compared to the incineration facility (up to 5 bar). Additionally, the gasification plant is located near a denser population, which increases public exposure to potential risks. Although the risks remain within acceptable limits, applying ALARP principles to minimise these risks and ensure safety is essential.

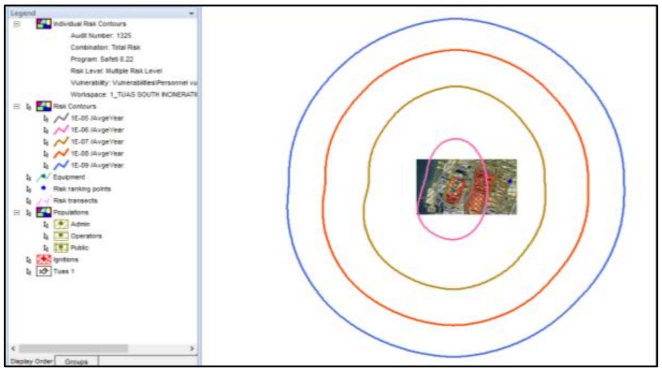

Figure 21 Total IR risk contour for incineration

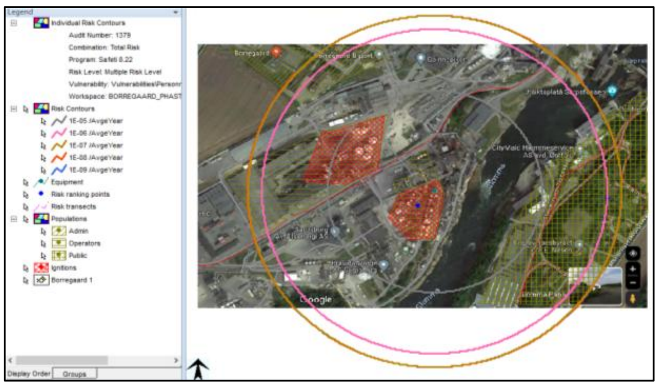

Figure 22 Total IR risk contour for gasification

Societal Risk Analysis

The societal risk is acceptable if the F-N curve is below the minimum criterion (yellow line). ALARP principles must be applied to mitigate risk if it falls between the minimum and maximum (red line). Exceeding the maximum criterion indicates intolerable risk, requiring system redesign. For the Borregaard 2 Gasification, Figure 23 shows that gasification involves both toxic and flammable risks. The F-N curve starts within the ALARP region but crosses into the intolerable zone, violating DOE Malaysia's risk criteria, which requires redesign. The top curve (Flammable-Night) starts at 1E-04/AvgYear and decreases to 0.001/AvgYear as fatalities rise from 1 to 40. Table 16 shows a total risk integral of 0.000586/AvgYear, with catastrophic ruptures potentially causing up to 25 fatalities from fireballs due to syngas release. The facility's proximity to a populated area increases the public risk, making these outcomes severe.

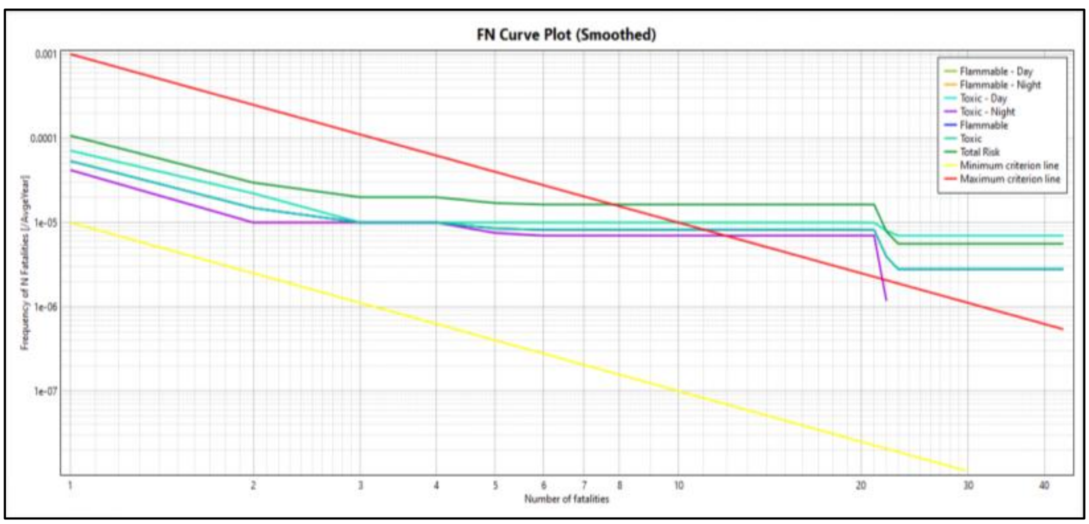

Figure 23 F-N curves for Borregaard gasification

Table 16 Total societal risk for Borregaard gasification

Total Risk Integral (/AvgYear)		: 0.000586		
Equipment	Scenario	Model Frequency (/AvgYear)	Average Fatalities	Risk Integral Percentage
Primary Gasifier	Catastrophic Rupture	1E-05	24.429	41.639
Oxidation Chamber		1E-05	24.491	41.745

Overall, the Societal Risk result shows that it is a high-risk facility. Implementing all possible risk management measures to further reduce the risk the facility poses is crucial. Table 17 below provides information about the risks associated with incineration and gasification processes. These risks are categorised into two types: indoor and outdoor vulnerability. The risk total represents the average risk per year.

For incineration, the indoor risk is 5.63E-06, well below the 1 in 100,000 threshold, indicating acceptable risk, while the outdoor risk is 2.19E-05, exceeding the threshold but still within the ALARP region, meaning it can be managed with mitigation measures. For gasification, indoor and outdoor risks are 1.93E-05 and 2.63E-05, respectively, both above the threshold but within ALARP, suggesting the need for risk reduction strategies, particularly outdoors. Incineration primarily poses environmental health risks from pollutant emissions, requiring effective control measures. Gasification introduces additional hazards from flammable syngas, which could cause flash fires or explosions if it leaks. Unlike gasification, incineration does not produce flammable gases but requires attention to emissions.

Regarding societal risk, the F-N curve for incineration is within the ALARP region, with a Total Risk Integral of 0.000178/AvgYear and a maximum of 8.5 fatalities in a catastrophic rupture. The public's Potential Loss of Life (PLL) is 3.07E-06/AvgYear. The F-N curve eventually moves into the unacceptable risk zone for gasification, with a Total Risk Integral of 0.000586/AvgYear and a maximum of 24.5 fatalities. The operator's PLL is 0.000267/AvgYear, and the public's PLL is 6.22E-07/AvgYear. Both technologies require strategies to mitigate risks.

Risk Reduction Strategies

Strategies for ensuring chemical process safety typically encompass a blend of inherent, passive, active, and procedural elements to minimise accident risks and guarantee secure facility operations, as outlined by Hendershot [33]. Inherent safety concentrates on selecting less hazardous chemicals and processes, simplifying operations to reduce failure, and designing equipment to endure potential loss. Passive safety employs physical barriers, containment systems, and engineered controls, while active safety utilises systems to monitor and respond to process conditions actively. Procedural safety involves training and management systems ensuring safe operation. By integrating these components into a comprehensive safety management system, WtE plants can effectively mitigate operational risks, safeguarding personnel, communities, and the environment. Several strategies are proposed to mitigate the risk of toxic gas release at Tuas South incineration, including engineering controls, advanced monitoring systems, safer material substitutes, and process simplifications. Passive measures such as exclusion zones, containment systems, and ventilation, along with active measures like emergency shutdown

Table 17 SAFETI analysis results for incineration

Risk Type	Risk Total (Avg/Year)	Outcome	Result
	Incineration		
Indoor Vulnerability	5.62838E-06	< 1 in 100000	Acceptable Region
Outdoor Vulnerability	2.19339E-05	> 1 in 100000	ALARP Region
	Gasification		
Indoor Vulnerability	1.93397E-05	> 1 in 100000	ALARP Region
Outdoor Vulnerability	2.62671E-05	> 1 in 100000	

systems and continuous monitoring, are recommended. Procedural measures involve enhancing maintenance programs and standardising protocols. Similarly, for Borregaard gasification, strategies to address hazards such as toxic gas release, fire, and explosion include smaller-scale gasifier designs, engineering controls, and safer materials. Passive and active measures, along with procedural improvements like comprehensive operating procedures and specialised training, are suggested to enhance safety and sustainability at both facilities [34]-[37].

CONCLUSION AND RECOMMENDATION

This study applied Quantitative Risk Assessment (QRA) using simulation software PHAST and SAFETI to assess risks at incineration and gasification plants. The incineration plant handles toxic materials, while the gasification plant deals with both toxic and flammable releases. PHAST simulations showed that incineration had longer downwind distances for toxicity release than gasification, with the furthest distance (5350 m) observed in the furnace stoker scenario. Incineration also showed higher toxicity release overall. The relationship between flash fire distances, radiation, and overpressure (up to 20 bar) revealed that gasification posed higher fire and explosion risks, as no flammability analysis was conducted for incineration. In SAFETI simulations, individual risk assessments for both plants indicated risks within As Low As Reasonably Practicable (ALARP) levels. For society, incineration was deemed to present acceptable risks, with a total risk integral of 0.000178 per year. In contrast, gasification reached unacceptable risk levels with a total risk integral of 0.000586. The highest average fatalities in catastrophic rupture scenarios were 8.5 for incineration (superheated boiler) and 24.5 for gasification (oxidation chamber). The operator was more impacted by gasification than incineration. Overall, incineration presented lower risks than gasification in both individual and societal risk assessments. The study emphasises the importance of risk reduction strategies, such as leak detection, ventilation, and emergency plans. Future studies should incorporate advanced modelling techniques like Computational Fluid Dynamics (CFD) and data analytics to improve QRA accuracy and enhance safety in Waste-to-Energy (WtE) facilities.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknologi PETRONAS for their invaluable support in completing this manuscript.

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